

## Chapter 3

# Lake bank filtration for water supply in Nainital

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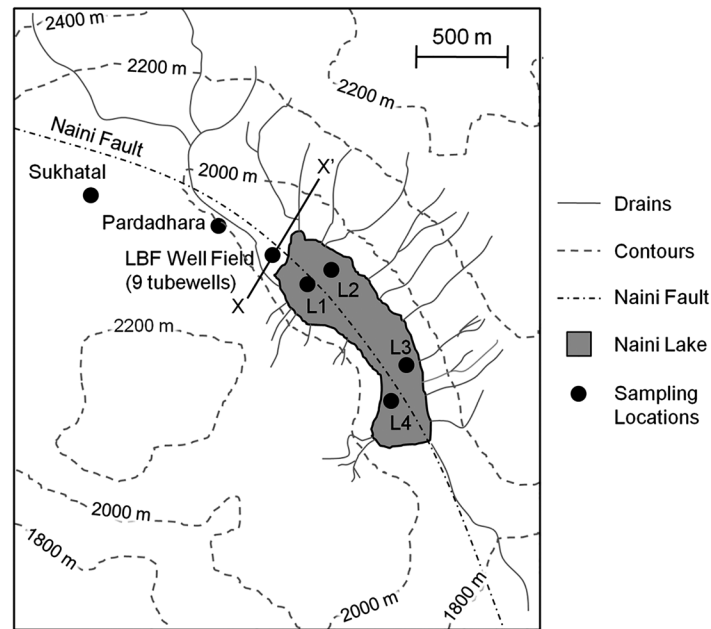
### 3.1 INTRODUCTION

As mentioned in the previous chapters, surface water bodies such as lakes and rivers have been and continue to be major sources of water supply. Alluvial aquifers hydraulically connected to a water course offer a relatively easy option for abstracting surface water with improvement in water quality in terms of turbidity, pathogens, and dissolved organics. This technology called bank filtration makes an important difference in implementations at lake banks and river banks. At lake banks, the colmation layer – the most important purification zone at the soil/water interface – is not disrupted by seasonal changes in water flows as in the case of river banks. This lake bank feature offers the advantage of a consistently higher attenuation of contaminants throughout the year than river banks. On the other hand, there are also potential problems at lake banks that may occur due to clogging.

Lake bank filtration (LBF) is used in many countries around the world for municipal water supply such as Germany, Finland, and the Netherlands. LBF wells at Lake Tegel in Berlin have been used for the city's drinking water supply for more than 100 years (Fritz *et al.*, 2002). In Finland, LBF schemes have been implemented on the island of Hietasalo in Lake Kallavesi and at the banks of lakes Vihnusjärvi and Vesijärvi (Miettinen *et al.*, 1994; Kivimäki *et al.*, 1998). In the Netherlands, an LBF scheme has been implemented along the deep gravel extraction reservoir De Lange Vlieter (Juhász-Holterman *et al.*, 1998), which is recharged with water from River Mass (also known as River Meuse). The travel times for bank filtrates to the LBF wells are estimated to be in the range of one week to a few months based on various tracers such as stable isotopes ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ), chloride, boron, and pharmaceutical residues (Massmann *et al.*, 2008; Miettinen *et al.*, 1994). Studies on the colmation layer in the littoral zones of Lake Tegel (Hoffmann & Gunkel, 2011) show that this biological zone in lakes extends to a depth of ~10 cm.

In Nainital town in the Himalayan region of India, an LBF scheme was developed at the bank of Lake Naini starting in 1990 (Figure 3.1). Nainital has one of the oldest piped water supply systems in the Kumaun region implemented in 1898. The development of Nainital's water supply has been described by Dash *et al.* (2008). The water was drawn from springs and pumped to higher elevations using steam engines, which were replaced by diesel engines in 1914. In 1955, increasing water demand led to pumping the lake water in addition to spring water. In 1985, a water treatment plant was installed for purification of the lake water to produce drinking water. To meet the increasing demand, seven tube-wells were installed adjacent to Lake Naini between 1990 and 2007 to abstract lake bank filtrate (Dash *et al.*, 2008). The abstracted filtrate was only chlorinated before supply. A water quality investigation by Dash *et al.* (2008) showed the LBF scheme to be more effective in coliform removal than the sand filtration in the water treatment plant. Subsequently, direct pumping of lake water and its purification was discontinued and in 2008 and 2009, five additional wells were constructed near the lake bank. By November 2011, one of the older wells constructed between 1990 and 2007 was dismantled, and two other tube-wells were shut down because of

operational problems; thus the LBF well field comprised nine production wells during the time period of present study. At the time of preparing this manuscript (August, 2014), the two non-functioning wells have been made operational and a total of eleven wells are in operation.



**Figure 3.1** Map of the region around Naini Lake (Based on GoogleMaps, 2014 and AHEC, 2002). X–X' shows the area for which a geological cross-section is shown in Figure 3.5.

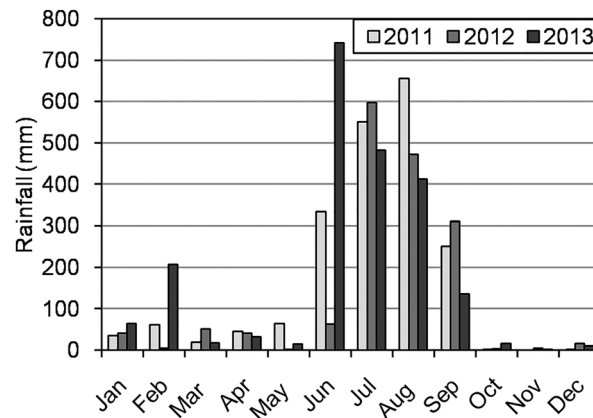
Due to being a popular tourist spot, the anthropogenic activities in Nainital have led to severe degradation of the Naini Lake over several decades as it became increasingly eutrophic (Pant *et al.*, 1981). The Macroenthic community in the lake has almost completely disappeared below a depth of 7 m (Gupta & Pant, 1983). Studies have been conducted on its water quality (Purohit and Singh, 1981), phytoplankton community (Sharma *et al.*, 1982), macrophytes (Purohit *et al.*, 1986), protozoa (Shukla & Gupta, 2001), predacious *Bdellovibrio*-like Organisms (Chauhan *et al.*, 2009), water and sediment geochemistry (Das *et al.*, 1995; Chakrapani, 2002; Purushothaman *et al.*, 2012), morphology and morphometry (Rawat, 1987), sediment accumulation (Das *et al.*, 1994), water balance (Kumar *et al.*, 1999), pesticides (Dua *et al.*, 1998), and heavy metal concentrations (Gupta *et al.*, 2010). Since 2007, several measures have been taken to conserve the lake and control its eutrophication. These measures included upgrading the town's sewer system to prevent any town wastewater from entering the lake, cleaning up and preventing solid waste from being dumped into the lake and, most importantly, introducing hypolimnetic aeration of the lake. After aeration, the algal and diatom population in the lake had decreased, and Cyaneophyceae (blue–green bacteria) had disappeared (Gupta & Gupta, 2012).

This chapter presents studies on water quality of the LBF wells, lake water and groundwater to assess its performance after recent changes in the Naini Lake, its catchment, and the LBF well field. The study was undertaken predominantly over a period of one and a half years during 2012–2013. Stable isotope analysis was done to assess the proportion of groundwater and bank filtrate in each well and the dynamics of the bank filtrate and groundwater in the LBF well field. The results were compared with previous data (Dash *et al.*, 2008) to assess the changes in water quality.

### 3.2 STUDY SITE

Lake Naini and the LBF system have been described in detail by Dash *et al.* (2008) and AHEC (2002). This section gives a brief overview of the site in light of recent changes in the system. Located in the Kumaun Himalayas in the State of Uttarakhand, India, Lake Naini is a kidney shaped water body. Nainital City, developed around the lake economically as well as socially, has a population of about 41,377 (Census of India, 2011). Additionally, the daily tourist influx in summer months averages around 5,000. The land-use of the lake catchment includes forests and shrubs (42%), buildings (41%), roads (2.1%), water bodies (10.3%), playgrounds (1.1%), and barren lands (3.5%).

Lake Naini is surrounded by steep mountain ranges from three sides and a downhill slope on the south-east side. There are several faults and fractures in the catchment of the lake. A fault called Naini Fault runs midway across the lake as shown in Figure 3.1. Most subsurface inflow to the lake takes place through the faults and fractures (AHEC, 2002). The lake is fed by about twenty water channels, only two of which are perennial open drains. Other water inputs to the lake come from direct precipitation, internal and underwater springs and subsurface groundwater flow from the surrounding mountain ranges. Rainfall is mostly restricted to the monsoon season from June to September during which about 90% of the annual precipitation occurs as shown in Figure 3.2. The year 2013 had unusually high rainfall in February and June, which was an exception in the non-monsoon period.



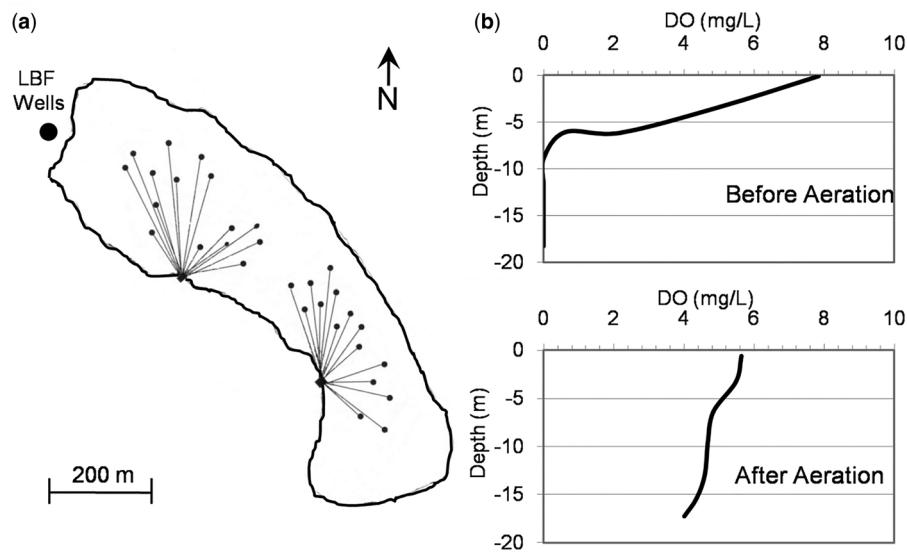
**Figure 3.2** Mean monthly rainfall in the Nainital district during 2011–2013 (IMD, 2013).

The water level in the lake is regulated with the help of sluice gates constructed at the south-east end of the lake. Excess water is discharged through sluices and then flows downhill as the Balia River. The capacity of the lake is progressively decreasing. Its volume was estimated to be  $7,425 \times 10^3 \text{ m}^3$  in 1899,  $6,808 \times 10^3 \text{ m}^3$  in 1969, and  $5,907 \times 10^3 \text{ m}^3$  in 1982 (Nachiappan *et al.*, 2002). Based on the sedimentation rates obtained from  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  dating techniques, Kumar *et al.* (1999) estimated the lake life as  $2,480 \pm 310$  years and  $2,160 \pm 80$  years, respectively. A brief summary of location, morphological, and meteorological data of the lake is given in Table 3.1.

**Table 3.1** Location, morphological and meteorological data for Lake Naini. Modified from Dash *et al.* (2008).

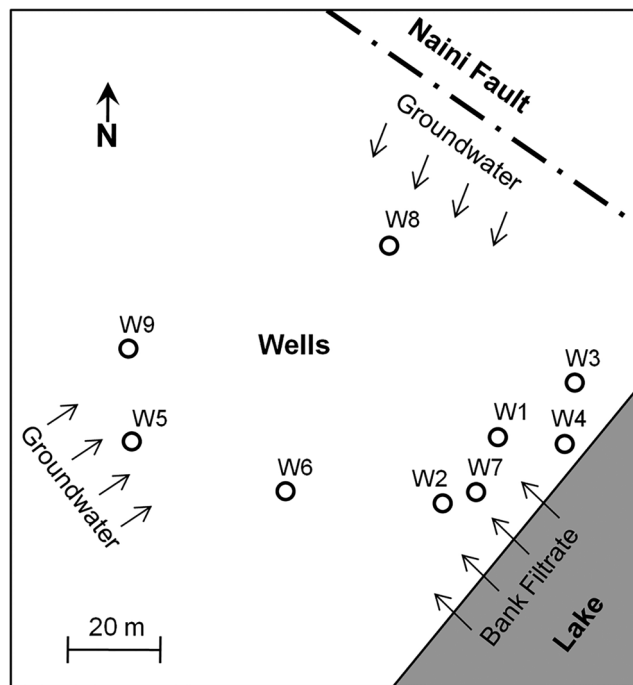
Parameter	Values	Parameter	Values
Altitude	1,937 m a.s.l.	Shoreline	3,630 m
Longitude	79°28' E	Volume of water	5,907,500 m <sup>3</sup>
Latitude	29°23' N	Annual rainfall	2,300 mm
Maximum length	1,432 m	Maximum air temperature	24.6 °C
Maximum breadth	423 m	Minimum air temperature	0.5 °C
Maximum depth	27.3 m	Maximum water temperature	25 °C
Mean depth	16.2 m	Minimum water temperature	10 °C
Surface area	0.48 km <sup>2</sup>	Mean water retention time (AHEC, 2002)	1.16 years
Catchment area	3.96 km <sup>2</sup>		

For hypolimnetic aeration, two sets of aeration units were installed in the lake in 2007 as shown in Figure 3.3a. Each unit has a set of 15 disk modules that release compressed air at a pressure of ~310 kPa at the bottom of the lake. Ozone is introduced along with the air to prevent clogging of the disk modules (Williams, 2007). The aeration has significantly changed the dissolved oxygen (DO) profile of the lake (Kumar, 2008) as shown in Figure 3.3b. Before aeration, the DO was close to 0 mg/L below a depth of 8 m. After aeration, the lake had a DO of about 4 mg/L down to the bottom. The DO in the bottom zones is maintained around 3–4 mg/L by controlling the aeration rate.



**Figure 3.3** (a) Locations of the aeration disks placed in Lake Naini. (b) Representative DO profile of the lake before aeration (on September 6, 2007) and after aeration (on October 22, 2007) (Kumar, 2008).

The LBF wells are located on the north-west bank of the lake as shown in Figure 3.4 and their construction details are given in Table 3.2. As of now (August, 2014), Nainital City has a water demand of about 14 MLD in winter and 18.5 MLD in summer. The LBF wells operate for 14–20 hours per day depending on the demand and are used to abstract about 12 MLD water in winters and 16 MLD in summers. The use of spring water from Pardadhara (Figure 3.1) for water supply continues. There is a seasonal lake called Sukhatal uphill along the fault which fills up with water during the rainy season but drainage through the faults and fractures rapidly dries up this temporary lake. A well has been drilled near the Sukhatal, specified here as Sukhatal tube well (Figure 3.1), to abstract groundwater for local supply.



**Figure 3.4** Location of wells W1-W9 with respect to the lake bank.

**Table 3.2** LBF wells and their parameters in order of increasing distance from the lake.

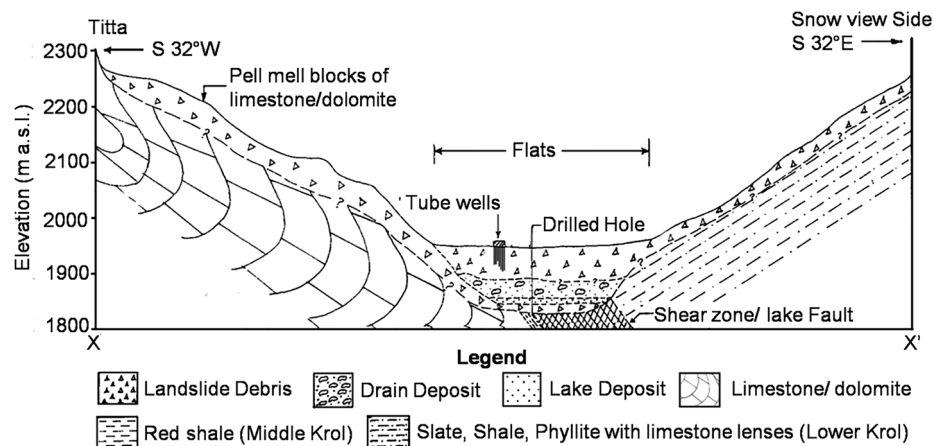
Well*	Distance from Lake [m]	Year of Installation	Discharge [L/min]	Elevation [m a.s.l.]	Drilling Depth [m]	Filter Screen Depths [m]
W4	4.3	1999	1,600	1,938.5	26.7	10.0–26.0
W7	11.7	2006	1,400	1,938.6	35.9	14.0–34.2
W3	14.5	2009	2,000	1,939.4	36.0	12.7–30.4, 33.2–35.4
W1	14.9	2008	2,000	1,939.0	35.9	13.7–23.6, 25.6–35.2
W2	14.9	2008	2,000	1,939.0	37.2	15.2–24.9, 26.9–36.6
W6	42.9	2006	2,200	1,939.4	36.7	14.0–35.5
W8	51.8	2008	1,800	1,939.7	35.8	15.3–35.1
W5	64.0	2000	2,400	1,939.8	33.4	10.9–33.2
W9	94.1	2008	1,800	1,940.0	37.0	14.1–23.7, 26.6–36.2

\*The wells are organized by increasing distance from the lake and well numbers are assigned by the water supply organization: Uttarakhand Jal Sansthan.

### 3.3 GEOLOGY OF THE TUBE-WELL SITE

A geological profile of the tube-well site is available from an investigatory drilling undertaken near the site to a depth of 132.6 m during 1975–1976 (Ashraf, 1978). The aquifer profile of the well field site has been described by Dash *et al.* (2008). The terrain around the tube-wells gently slopes and consists of debris from recurrent landslides that took place from 1867–1924. The aquifer consists of silty boulders, rock fragments, shale/slate, sand, and clay up to a depth of 50 m, followed by drain deposits, tree trunks, and lake deposits up to 100 m and slide debris for the next 17 m, below which is the bedrock consisting of red and green shale and slate of Middle Krol Formation.

The geology of the area is characterized by a number of folds and faults. Sharma (2001) has mapped the trace of the lake fault shear zone close to the tube-well site to a depth of ~116 m (Figure 3.5). The mountains consist of slates, marls, carbonates, limestones, dolomites, sandstone and conglomerates (Valdiya, 1980, 1988). The aquifer at the LBF well site consisting of irregular collapsed rocks contrasts the weathered sediments and silt making up aquifers in other cases. Based on grain size distribution by sieve analysis of aquifer soil obtained during drilling of well W6, hydraulic conductivities at different depths were estimated by Hazen's method to be 300–460 m/d with an average value of 327.5 m/d (Dash *et al.*, 2008). Pumping tests with Boulton's analysis yielded a hydraulic conductivity of ~275 m/d for wells near the lake and ~430 m/d for well W5 located far from the lake (Sandeep, 2011). This aquifer extends to a depth of about 36 m followed by a clay layer. Based on the hydraulic conductivities, travel times of the bank filtrate to wells W4 and W5 are estimated to be 1–2 days and 11–19 days, respectively.

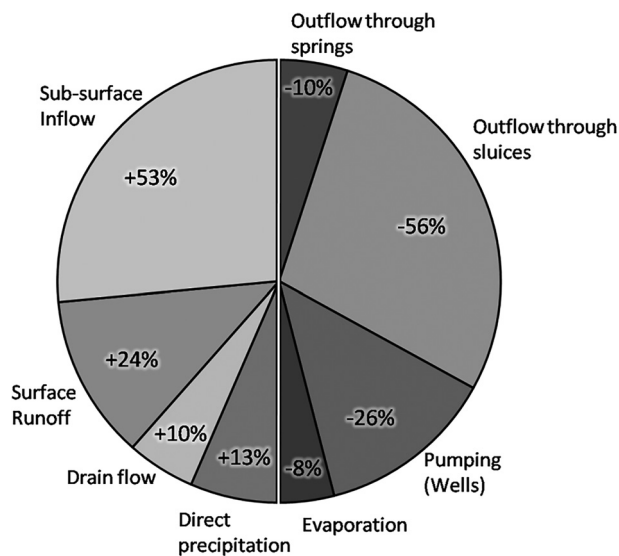


**Figure 3.5** Geological cross-section (X–X' in Figure 3.1) across tube-well/waterworks site near the northern edge of Lake Naini. Modified from Sharma (2001).

### 3.4 WATER BALANCE

A water balance study of Lake Naini was undertaken by the National Institute of Hydrology from 1994–2001 and a conceptual model was developed (AHEC, 2002). The conceptual model was validated using techniques such as isotope mass balance and chloride mass balance (Nachiappan *et al.*, 2002). Groundwater movement in the lake catchment preferentially takes place along faults and fractures towards the lake. Sukhatal, situated in the catchment of Lake Naini, does not have any surface outflow. Because of the proximity of the lake fault to Sukhatal, most of the water seeps underground and recharges Lake Naini. Sub-surface outflow from the lake mainly takes place through the epilimnion zone.

Average percentages of different components of water inputs and outputs to the lake on an annual basis are shown in Figure 3.6. Average quantities of annual water loss or gain by Lake Naini through different processes have been found to be  $7.7 \times 10^6 \text{ m}^3$ . The subsurface inflow, pumping from tube-wells, and outflow through sluices are quantitatively prominent processes in water exchange between the lake and its catchment. The evaporation loss, direct rainfall over the lake surface area, outflow through springs and inflow through the drains are minor components.



**Figure 3.6** Water balance components and their average annual percentages for Lake Naini (based on Nachippan *et al.*, 2002 and AHEC, 2002). Positive and negative values represent inflows to and outflow from the lake, respectively.

### 3.5 METHODOLOGY

#### 3.5.1 Sample collection

Water samples were collected from the lake and the LBF wells almost monthly from April 2012 to November 2013. Groundwater samples were collected from Pardadhara from Jan 2013 to Nov 2013 and from Sukhatal from February 2013 to November 2013. A few samples from the lake and LBF wells for coliform studies were also collected from January to May, 2011. Lake water samples were collected from ~0.5 m below the lake surface. Electrical conductivity (EC), pH, temperature, and dissolved oxygen (DO) were measured on-site using a portable multi-parameter probe (HQ40d, Hach, Loveland, USA). Well water samples were collected while the pumps were in operation for supply.

For the analysis of dissolved ions, water samples were collected in 1,000 mL polyethylene and polypropylene bottles. Samples for  $^{18}\text{O}$  isotope analyses were collected in 15 mL polypropylene bottles ensuring that no air bubbles were trapped in the bottle during collection. Samples for bacteriological analysis were collected in sterilized glass bottles. Samples were stored cool ( $4^\circ\text{C}$ ), in the dark and transported to the laboratory at IIT Roorkee for further analysis within 24 hours.

#### 3.5.2 Sample analysis

Total and faecal coliform counts in the samples were determined by the multiple tube fermentation technique. For the analysis of dissolved ions and dissolved organic carbon (DOC), the samples were filtered with  $0.22 \mu\text{m}$  size filter (Millipore,



GVWP). The ions (sodium, potassium, ammonium, calcium, magnesium, chloride, fluoride, nitrate, nitrite, sulphate, and total phosphate) were determined by ion chromatography (Metrohm, AG-861). DOC was measured using TOC-V<sub>CSN</sub> Total Organic Carbon Analyser (Shimadzu). UV absorbance (UV-A) at 254 nm was measured using DR5000 spectrophotometer (HACH) using a 10 mm quartz cell. Alkalinity was determined by titration with N/50 H<sub>2</sub>SO<sub>4</sub> (aq.) with bromocresol green as the indicator. All procedures for sampling, transportation, storage, and analyses were in accordance with the procedures given in Standard Methods (APHA *et al.*, 2005).

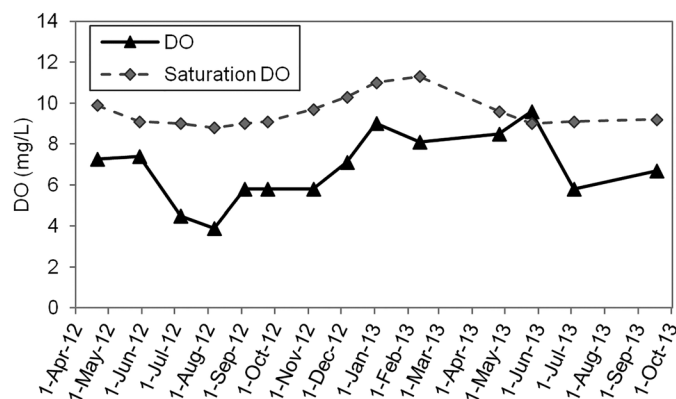
Isotopic analysis for  $\delta^{18}\text{O}$  in H<sub>2</sub>O in the samples was done at National Institute of Hydrology, Roorkee (India) using GV Isoprime Dual Inlet Isotope Ratio Mass Spectrometer. For  $\delta^{18}\text{O}$  analysis, 400  $\mu\text{L}$  of water samples were equilibrated for 7 hours with CO<sub>2</sub> reference gas. The measured delta ( $\delta$ ) values are given with respect to Vienna Standard Mean Ocean Water. The precision of measurement for  $\delta^{18}\text{O}$  is  $\pm 0.1\text{‰}$ .

### 3.6 RESULTS AND DISCUSSION

The performance of the LBF system at Lake Naini was evaluated in terms of two criteria: the quality of water abstracted in terms of drinking water standards and the fraction of lake water abstracted in the wells. Mixing of bank filtrate with ground water in the LBF wells was assessed by stable isotope analysis. This section first briefly discusses the spatial and seasonal variations in the lake water quality during the study period and then presents the results of isotopic investigations and water quality analysis.

#### 3.6.1 Spatio-temporal variation in lake water quality

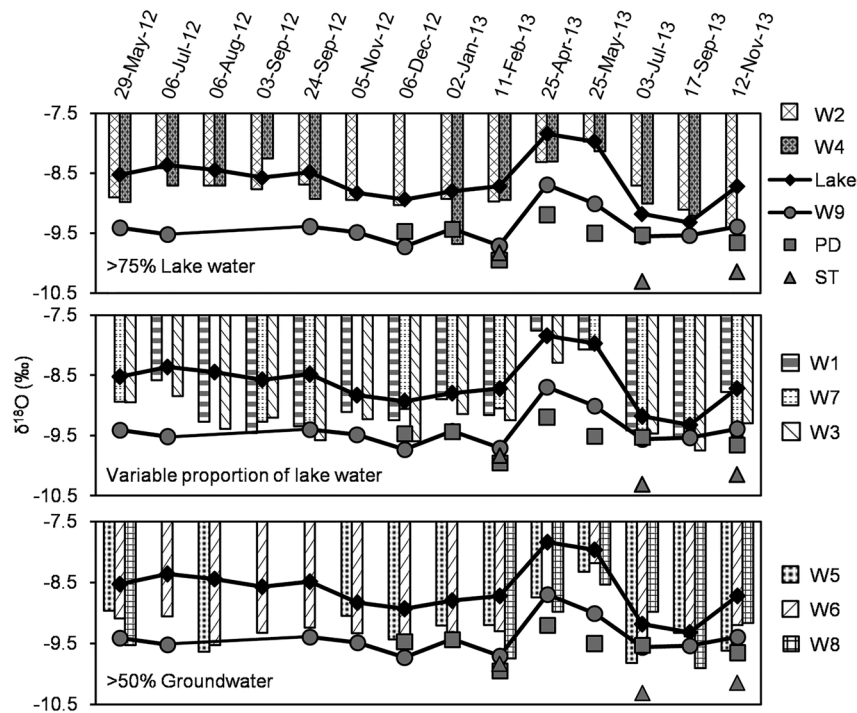
The most important parameter of lake water quality is DO. During the study period, the surface DO in Lake Naini underwent seasonal cycles as shown in Figure 3.7. From June to November, it dropped to 4–6 mg/L. From December to May, it reached 7–10 mg/L, close to its saturation value. The temperature of the lake surface water varied between 10°C and 22°C. EC of the lake water also showed annual variation between 570–630  $\mu\text{S}/\text{cm}$  with a slight decrease in the monsoon season and an increase in winter. The variations in EC between various points (L1-L4, Figure 3.1) on the lake were up to  $\sim 60 \mu\text{S}/\text{cm}$ . Point L1, shown in Figure 3.1, was chosen as a representative point for infiltrating lake water in LBF wells because of its proximity to the wells.



**Figure 3.7** Dissolved oxygen (DO) concentration of the lake at its surface and its saturation concentration at the water temperature as a function of time.

#### 3.6.2 Proportion of bank filtrate and groundwater in the wells

The  $\delta^{18}\text{O}$  values for the waters from various sites are presented in Figure 3.8. The lake was predominantly fed by groundwater but because of a long retention time of  $\sim 1$  year and hence prolonged evaporative enrichment, the lake water was isotopically richer in  $^{18}\text{O}$  than the groundwater. Among the well waters, the  $\delta^{18}\text{O}$  values of W9 were the lowest throughout the year and were comparable with the spring water samples from Pardadhara. Due to lack of groundwater data for the complete study period, W9 values were considered as indicative of the groundwater isotopic values (Figure 3.8). It is consistent with the expectation that W9 would abstract the highest portion of ambient land-side groundwater as W9 is located farthest from the lake at a distance of 94 m (Figure 3.4, Table 3.2).



**Figure 3.8** Plots of  $\delta^{18}\text{O}$  values for the lake water, various wells, and the groundwater sources.

The  $\delta^{18}\text{O}$  values of the well waters and their temporal variations could be categorized into the following three groups, represented by the three graphs in Figure 3.8:

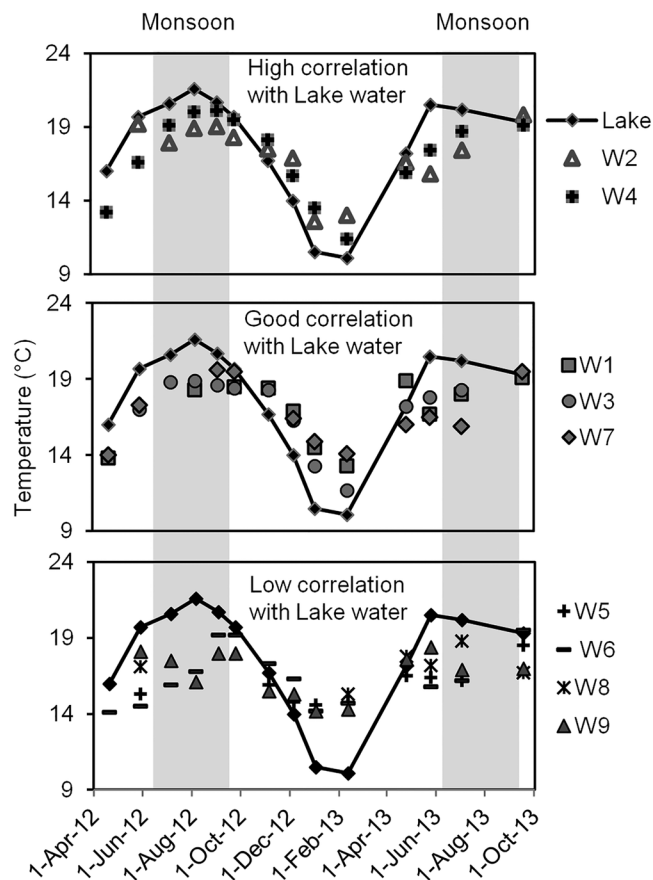
- The first group consisting of wells W2 and W4 had  $\delta^{18}\text{O}$  values similar to the lake water almost throughout the year, suggesting that these wells continuously drew bank filtrate. Average  $\delta^{18}\text{O}$  values for each well calculated using the two-component mixing model, shown in Table 3.3, suggest that the two wells abstracted ~80% bank filtrate.
- The second group consisting of wells W1, W3, and W7 had waters isotopically similar to the groundwater during the monsoon period and similar to the lake water during the non-monsoon period. Average values (Table 3.3) indicate that W1 and W7 abstracted 50–75% bank filtrate annually while well W3 abstracted only ~40% bank filtrate. These results are surprising particularly because wells W1, W2, and W3 are located at about the same distance from the lake bank but abstracted such different proportions of bank filtrate. Such anomalous observations suggest the presence of subsurface seepage from the Naini Fault or highly irregular flow of groundwater in the lake bank aquifer. The proposed groundwater flow from the fault seepage is indicated in Figure 3.4, where higher groundwater proportion in W3 can be explained by its proximity to the fault.
- The third group consists of wells W5, W6, W8, and W9, which all had isotopic signatures consistently similar to the groundwater, showing that these wells predominantly abstracted groundwater throughout the year. Average values (Table 3.3) indicate that W5, W6, and W8 abstracted 25–50% bank filtrate while W9 abstracted <25% bank filtrate. These conclusions about the bank filtrate proportion are also supported by the water quality results (*vide infra*).

Temperature profiles of water in the wells and their correlation with the lake temperature (Figure 3.9) were also different for the three groups of wells. Lake surface temperature showed a smooth temperature variation corresponding to the seasonal changes. Temperatures of the wells W2 and W4 varied similar to the lake with a slight delay in the maxima of about 1 month. This delay might be less than one month, but it cannot be determined exactly because no sample was taken during this period. This delay – much longer than the travel time of water – was likely caused by temperature retardation by the aquifer material. Temperature profiles of the wells W1, W3, and W7 were also similar to the lake but had a slightly lower correlation with the lake as compared to wells W2 and W4. The temperature equilibration effect of the aquifer is likely to reduce the temperature difference between the first and second groups of wells. Wells W5, W6, W8, and W9 had poor correlation with the lake water. These wells also had a very narrow temperature range, characteristic of groundwater – consistent with the high groundwater proportion in these wells.



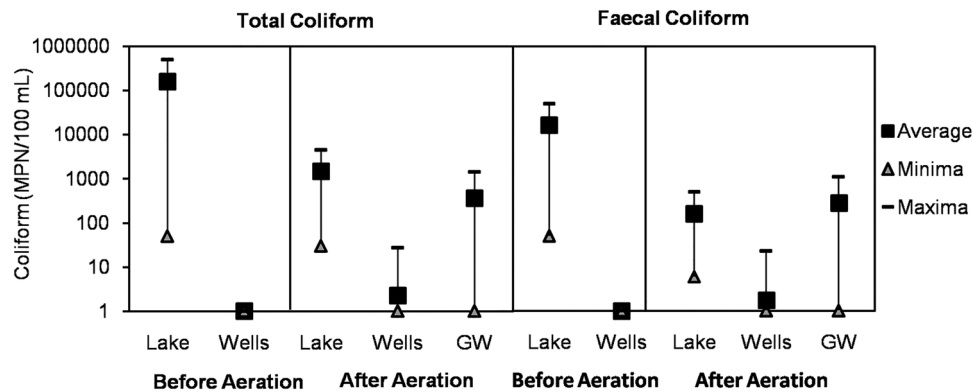
**Table 3.3** Percent bank filtrate in various wells based on average  $\delta^{18}\text{O}$  values for the lake water, various wells and groundwater sources.

Water Source	$\delta^{18}\text{O}$ [‰]	Percent Bank Filtrate [%]
Lake	-8.60	—
W2	-8.78	83
W4	-8.81	80
W1	-8.97	65
W7	-9.08	54
W3	-9.23	40
W5	-9.21	42
W6	-9.24	39
W8	-9.26	37
W9	-9.40	24
Groundwater (Pardadhara & Sukhatal)	-9.65	—

**Figure 3.9** Temperature profiles of the lake and well waters.

### 3.6.3 Attenuation of coliforms, turbidity and dissolved organics

After aeration, the coliform counts, the turbidity and the concentrations of organics reduced significantly in the lake. Figure 3.10 shows the total and faecal coliform counts in the lake water before and after aeration. The coliform MPN counts in the lake reduced by two orders of magnitude to low levels of  $\sim 1,000$  MPN/100 mL. This reduction in the coliform counts is also likely to be due to disinfection by ozone used in the aerators.



**Figure 3.10** Total and faecal coliform in the lake, the wells, and the groundwater sources (includes Pardadhara and Sukhatal) before (Dash *et al.*, 2008) and after aeration (2011, 2012–2013). The five sets of samples for each parameter have  $n$  values 72, 30 (5 wells), 18, 116 (9 wells), and 8, respectively.

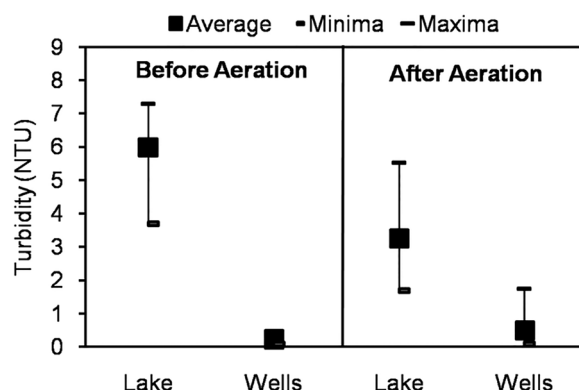
As mentioned before, the LBF wells had delivered coliform-free water even before aeration (Dash *et al.*, 2008). The median and range of the coliform values for different sources during the recent sampling period (2011 to 2013) is given in Table 3.4. Pardadhara water often showed coliform contamination. The wells were largely free of coliform except for a breakthrough that was observed in summer months. During this period, coliform level was at its highest in the lake, a few wells, and Pardadhara. The highest level of contamination was observed in wells W5, W9, and W2. Contamination in wells W1 and W4 was much lower, indicating that the contamination came from the groundwater or localized infiltration of contaminated water and not from the bank filtrate.

**Table 3.4** Variation of total and faecal coliform counts in various sources. The entries represent median (range).

Sample (n)	Total Coliforms [MPN/100 mL]	Faecal Coliforms [MPN/100 mL]	No. of Samples with Total Coliforms > 2 MPN/100 mL
Lake (18)	1,600 (30–4,500)	141 (6–500)	18
W4 (13)	<2 (<2–17)	<2	2 (Jun. 2012, Sep. 2012)
W2 (17)	<2 (<2–1,553)	<2 (<2–1,553)	1 (Jul. 2013)
W1 (18)	<2 (<2–17)	<2 (<2–3)	2 (Jun. 2012; Jul. 2013)
W7 (15)	<2 (<2–36)	<2 (<2–23)	3 (Jan. May, 2011; Jul. 2013)
W3 (18)	<2 (<2–70)	<2 (<2–16)	2 (Jun. 2012; Jul. 2013)
W6 (17)	<2	<2	–
W8 (7)	<2 (<2–27)	<2 (<2–14)	3 (Feb. 2011; Jul.–Sep. 2013)
W5 (6)	<2 (<2–2,420)	<2 (<2–2,420)	1 (Jul. 13)
W9 (17)	<2 (<2–2,420)	<2 (<2–2,420)	5 (Feb.–Mar. 2011; Jul.–Nov. 2013)
Pardadhara (4)	709 (5–1,414)	561 (<2–1,120)	4 (May–Nov. 2013)
Sukhatal (4)	<2	<2	–

It is important to note that the well W6 still was not coliform contaminated while other wells on both sides occasionally were. This observation suggests that W6 gets a stream of groundwater that did not pass through wells W5 and W9 (Figure 3.4). Apparently, the groundwater flow direction from the hills on the west is towards the northeast as shown in Figure 3.4.

The turbidity of the lake decreased from 3.7–7.3 NTU before aeration (Dash *et al.*, 2008) to 1.7–5.5 NTU post aeration as shown in Figure 3.11. The turbidity in the wells monitored earlier had been consistently below 1 NTU. During the present sampling, the turbidity of the well water was 0.2 NTU most of the time, but occasionally it rose above 1 NTU. The mean turbidity and its range for various waters are given in Table 3.5. The turbidity in the wells, however, was within the limits for drinking water of 5 NTU according to the Indian standards BIS-10500 (2012).



**Figure 3.11** Turbidity in the lake and wells before (Dash *et al.*, 2008) and after aeration (2012–2013).

**Table 3.5** Mean (range) of turbidity, DOC, and SUVA values for various water sources. Single observations with values outside the normal range are mentioned in remarks column.

Sample	Turbidity [NTU]	DOC [mg/L]	SUVA [L/(mg m)]	Remarks
Lake	3.3 (1.7–5.5)	3.1 (1.2–4.7)	1.3 (0.7–2.5)	
W4	0.5 (0.2–1.3)	1.7 (0.8–3.6)	0.8 (0.3–1.7)	
W2	0.6 (0.2–1.2)	1.7 (0.6–3.7)	1.2 (0.3–1.4)	
W1	0.5 (0.1–1.2)	1.4 (0.6–3.8)	0.8 (0.3–1.4)	
W7	0.6 (0.2–1.8)	1.6 (0.6–3.2)	1.0 (0.2–2.2)	
W3	0.5 (0.2–1.0)	1.7 (0.5–3.6)	0.9 (0.3–1.3)	
W6	0.4 (0.2–1.2)	1.4 (0.4–3.3)	1.1 (0.1–2.3)	
W8	0.6 (0.2–0.9)	1.4 (0.4–3.2)	0.6 (0.2–1.9)	
W5	0.4 (0.2–1.1)	1.5 (0.6–3.5)	0.8 (0.2–2.4)	High turbidity (3.1 NTU) in Nov. 2013
W9	0.6 (0.1–1.6)	1.4 (0.4–3.1)	0.5 (0.2–1.1)	High SUVA (4.4 L/(mg m)) in Jul. 2013
Pardadhara	0.7 (0.5–1.0)	1.1 (0.4–3.2)	1.4 (0.1–3.0)	High turbidity (5.7 NTU) in Apr. 2013
Sukhatal	1.4 (1.2–1.7)	1.0 (0.3–1.6)	1.2 (0.3–1.7)	

The organics concentration was low in both the lake and the wells. The mean UV-A of the lake had been 0.059/cm before aeration, which was now reduced to 0.035/cm. Wells had UV-A consistently below 0.020/cm, except for W5 and W9 that had an increase in UV-A during monsoon of 2013. The LBF wells also had much lower average DOC of ~1.6 mg/L than the lake (Table 3.5). Specific ultraviolet absorbance (SUVA) values of well waters (Table 3.5) were slightly lower than the lake water, suggesting a slight decrease in aromatic compounds (Weishaar *et al.*, 2003) in the wells compared to the lake. Since wells W2 and W4 were receiving almost completely bank filtrate, we can estimate that bank filtration led to DOC reduction of 19% to 76% with a mean reduction of 52%.

### 3.6.4 Ionic composition of waters

The lake water had an average EC of 598  $\mu\text{S}/\text{cm}$  – lower than the groundwater (Table 3.6), likely because of mixing of groundwater with low conductivity rainwater and surface run-off. The EC of the wells varied from 630  $\mu\text{S}/\text{cm}$  to 900  $\mu\text{S}/\text{cm}$ , with significant differences between the three groups of wells. The first group of wells, W2 and W4, had an EC ~20  $\mu\text{S}/\text{cm}$  higher than that of lake water with much lower seasonal variation than the lake. The lower seasonal variation may be due to averaging effect of bank filtrate stored in the aquifer. The second group of wells, W1, W3, and W7 showed higher conductivity than the lake water by about 100–200  $\mu\text{S}/\text{cm}$ . Their EC values were also comparable to the groundwater samples from Sukhatal and Pardadhara. The third group of wells, W5, W6, W8, and W9, had EC values that were consistently 250–300  $\mu\text{S}/\text{cm}$  higher than the lake water and 100–150  $\mu\text{S}/\text{cm}$  higher than the groundwater samples. Such high differences observed consistently in EC values indicate that either there is high mineralization of groundwater in the aquifer around these wells or that the groundwater

coming to these wells is different than the groundwater at Pardadhara and Sukhatal. The range of seasonal variation in EC was also different for wells W9, W5, and W6, which supports the latter possibility and is consistent with the proposed groundwater flow direction shown in Figure 3.4. The differences in conductivities in the first group of wells, W2 and W4, and second group of wells, W1, W3, and W7, located very close to each other further supports the hypothesis of groundwater mixing rather than mineralization from the surrounding aquifer.

**Table 3.6** Mean (range) concentrations of major ions in various water sources.

Source	EC [ $\mu\text{S/cm}$ ]	Na <sup>+</sup> (mg/L)	K <sup>+</sup> [mg/L]	Ca <sup>2+</sup> [mg/L]	Mg <sup>2+</sup> [mg/L]
Lake	598 (498–698)	11 (7–14)	6 (3–9)	51 (38–80)	42 (37–50)
W4	633 (588–660)	13 (11–18)	6 (3–7)	55 (42–82)	47 (40–54)
W2	647 (552–705)	11 (9–14)	6 (4–9)	58 (46–84)	45 (36–53)
W1	697 (617–817)	15 (11–22)	6 (5–8)	60 (48–83)	49 (37–56)
W7	685 (610–862)	14 (10–19)	6 (4–8)	62 (47–84)	49 (36–57)
W3	708 (643–832)	16 (12–24)	6 (4–7)	63 (43–92)	55 (43–62)
W6	795 (688–894)	15 (11–19)	6 (4–8)	72 (43–95)	60 (44–68)
W8	823 (749–893)	20 (11–29)	6 (5–7)	75 (63–105)	56 (46–72)
W5	794 (693–915)	14 (10–22)	5 (4–7)	74 (62–99)	57 (42–66)
W9	844 (788–882)	15 (10–22)	6 (5–7)	75 (63–105)	63 (50–71)
Pardadhara	724 (683–766)	10 (7–13)	6 (4–13)	73 (62–110)	50 (46–58)
Sukhatal	693 (675–702)	9 (7–11)	6 (4–7)	73 (56–89)	50 (46–53)
Source	Cl <sup>-</sup> [mg/L]	NO <sub>3</sub> <sup>-</sup> [mg/L]	SO <sub>4</sub> <sup>2-</sup> [mg/L]	Alkalinity [mg/L]	Hardness [mg/L of CaCO <sub>3</sub> ]
Lake	8 (6–9)	6 (2–16)	91 (74–109)	213 (189–319)	302 (248–361)
W4	10 (8–18)	4 (0.4–11)	95 (72–109)	226 (196–239)	333 (273–378)
W2	8 (7–10)	4 (ND–6)	94 (68–147)	233 (186–276)	334 (273–370)
W1	12 (9–18)	13 (1–22)	100 (66–135)	255 (232–310)	356 (316–398)
W7	10 (8–13)	6 (2–15)	103 (98–165)	269 (240–318)	363 (301–408)
W3	11 (9–19)	13 (1–32)	105 (75–121)	251 (214–288)	385 (317–488)
W6	12 (9–16)	14 (2–31)	133 (98–165)	273 (234–324)	435 (316–478)
W8	14 (10–21)	11 (<0.5–34)	121 (107–137)	287 (252–333)	424 (362–502)
W5	10 (8–19)	10 (<0.5–22)	129 (96–176)	264 (260–268)	420 (362–463)
W9	12 (9–13)	14 (<0.5–28)	142 (121–158)	281 (240–301)	448 (384–495)
Pardadhara	9 (7–12)	13 (12–14)	136 (111–156)	259 (246–265)	403 (362–467)
Sukhatal	11 (9–14)	11 (9–14)	127 (110–141)	265 (238–312)	391 (357–442)

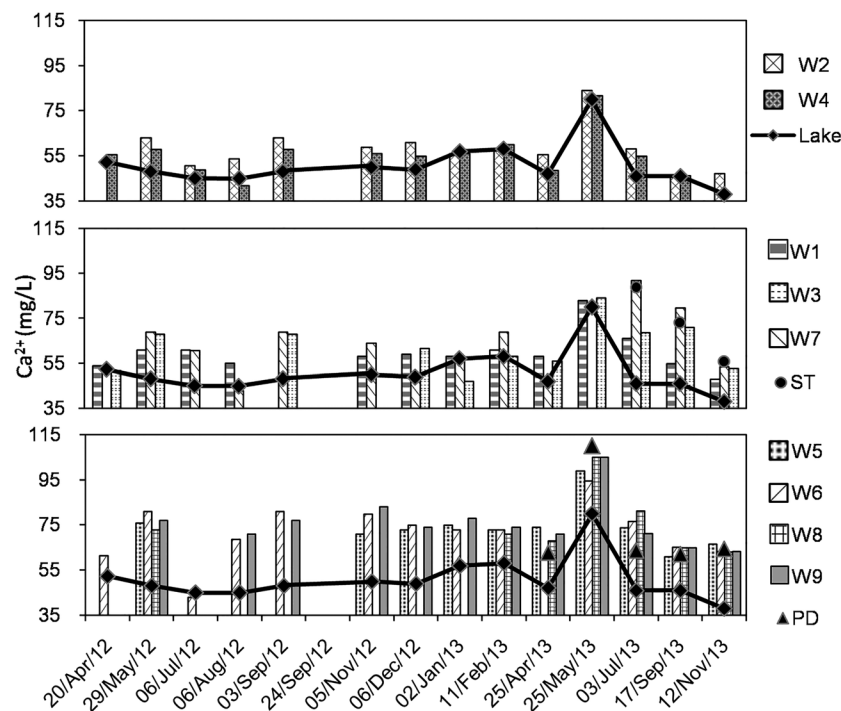
The lake and Sukhatal waters were predominantly alkaline with average pH values of 8.0 and above, while the well waters and Pardadhara were less alkaline with pH between 7.0 and 8.0. There were no significant differences among pH values of various wells, suggesting that the pH was largely determined by the aquifer and not the proportion of bank filtrate.

In terms of ionic composition, the lake, wells, and ground waters contained predominantly calcium, magnesium, sulphate and hydrogen carbonate in major amounts and sodium, potassium, chloride and nitrate in smaller amounts (Table 3.6). This is consistent with the findings of previous researchers (Nachiappan & Kumar, 1999; Chakrapani *et al.*, 2002), who ascribed the presence of limestone, dolomite, and other carbonates as sources for calcium, magnesium, and hydrogen carbonate ions; silicate minerals as source for sodium and potassium ions; and oxidation of pyrite minerals as a source for sulphate ions. Small amounts of chloride and nitrate are ascribed to sewage, and forest and small agricultural run-off. The hardness (Table 3.6) followed the same pattern as EC.

The concentrations of calcium and magnesium often exceed the desirable limits of 75 mg/L and 30 mg/L, respectively, for drinking water as per Indian drinking water standards BIS-10500 (2012). However, the concentration values remained within the maximum permissible limits of 200 and 100 mg/L, respectively, prescribed in BIS-10500 (2012) for the situations where an alternative source of water supply is not available. Consequently, the hardness values in the wells were also above the

desirable limits for drinking water (Bureau of Indian Standards, 2012), but were lower than the maximum permissible limit prescribed when an alternative source is not available.

Monthly variations in the concentrations of calcium, magnesium, and alkalinity, shown in Figures 3.12–3.14, had different patterns for the three groups of wells. These differences were not so pronounced for other ions. Wells W2 and W4 had calcium and magnesium concentrations similar to and alkalinity slightly higher than the lake water. In the second group of wells W1, W3, and W7, the values of the three parameters were higher than in the lake during the summer and monsoon months but comparable to those of the lake during other times. These observations were consistent with the variations in bank filtrate proportions in these wells. The concentrations in the third group of wells, W5, W6, W8, and W9, were much higher than the lake and comparable to the groundwaters. In general, calcium and magnesium concentrations in the lake and the bank filtrate decreased during the summer and monsoon periods and remained roughly constant in the groundwater.



**Figure 3.12** Monthly variations of calcium ( $\text{Ca}^{2+}$ ) concentration in various waters.

In spite of different values among various water sources, the calcium:magnesium molar ratio for all the sources studied lied around 0.75. This ratio is indicative of predominantly magnesium-containing minerals such as dolomite contributing to the mineralization of the water. Compared to the water quality of these sources before aeration (Dash *et al.*, 2008), this ratio has increased after aeration. Calcium concentrations in the waters have increased by about 10–15 mg/L, and magnesium concentrations have decreased by 5–10 mg/L. There was no significant difference in the concentration values of other ions before aeration and the values measured during the sampling campaign.

In general, the observations show that bank filtrate had low mineral content (comparable to the lake water) and better water quality in terms of organics, turbidity, and coliforms. The groundwater showed occasional contaminations. Therefore, wells W2 and W4 should be pumped more to obtain more of (better quality) bank filtrate. Abstraction from other wells can be regulated with seasonal changes to obtain larger amount of bank filtrate. Compared to the LBF well field in 2001 when water balance study was undertaken (Figure 3.6), there are more wells now, but the additional wells abstract mostly groundwater. As mentioned in Section 3.4, LBF wells in 2001 pumped 26% of the lake water output and 56% of the lake outflow was through sluices. Since evaporation and subsurface drainage cannot be prevented, LBF wells can extract a maximum of 82% of the lake outflow. Beyond this limit, water abstraction may not remain sustainable and would reduce the water quantity in the lake and groundwater level in the region. Based on a lake volume of 5,907 ML (5,907,000  $\text{m}^3$ ) and a mean retention time of 1.16 years (Table 3.1), this quantity turns out to be ~13.9 MLD. Of the current water abstraction of 12–16 MLD (Section 3.2), since LBF wells abstract ~40–50% bank filtrate on average, the quantity of bank filtrate abstraction can be increased only by up to a factor of 2.

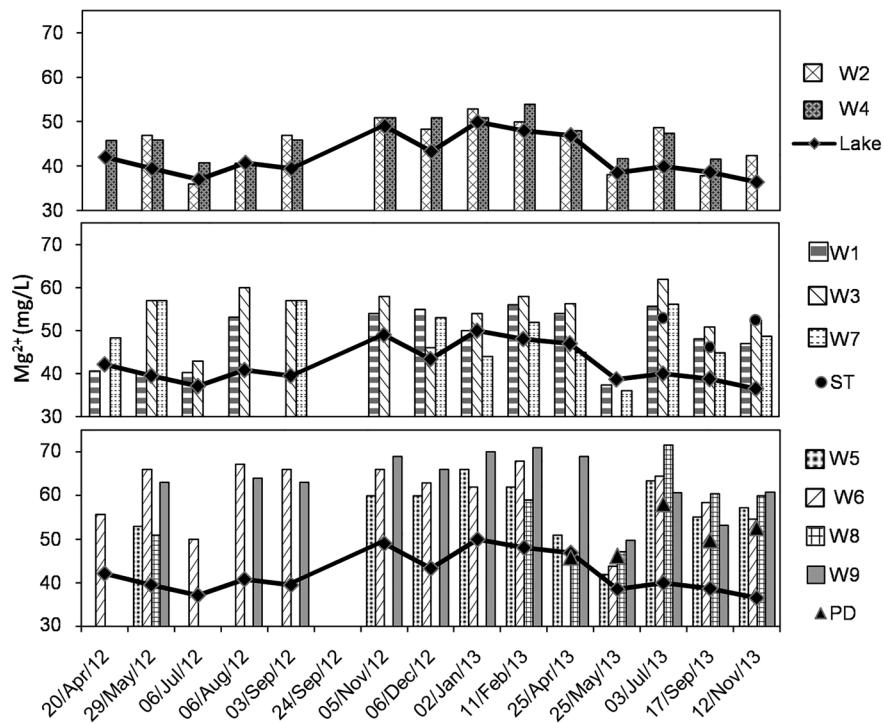


Figure 3.13 Monthly variations of magnesium ( $Mg^{2+}$ ) concentration in various waters.

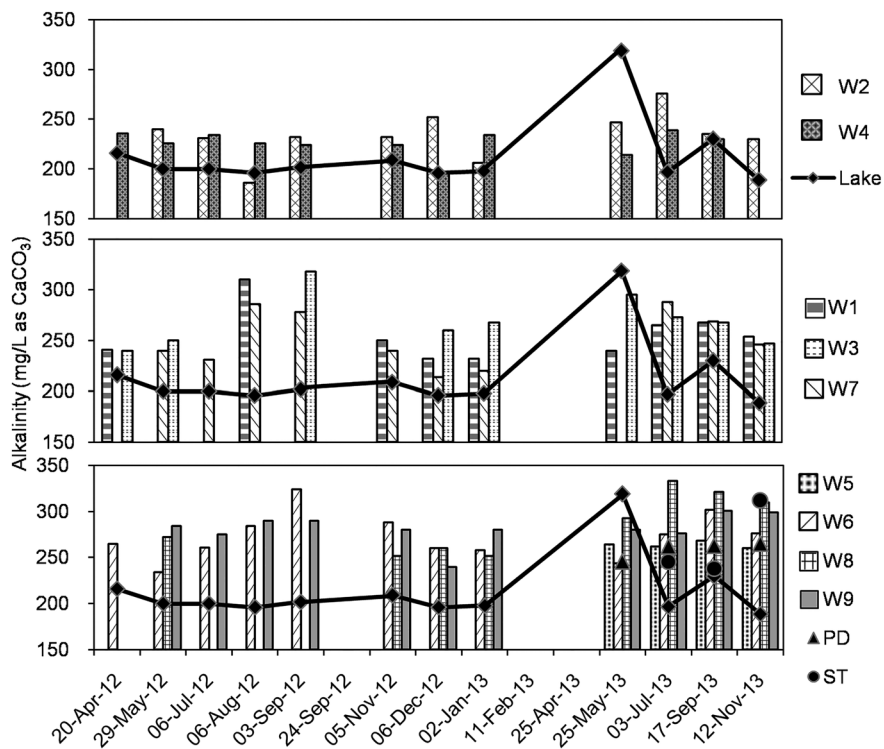


Figure 3.14 Monthly variations of alkalinity in various waters.



This study also showed that even though LBF systems are highly effective, groundwater dynamics can have a strong impact on the quality of water that is abstracted from the LBF wells. Local geology, hydrology, seasonal variations in groundwater dynamics, and potential impact of anthropogenic activities in the catchment need to be studied for effective decision making on LBF abstraction systems.

### 3.6.5 Comparison with previous literature

These conclusions about the proportions of bank filtrate in the wells are quite different from that of Nachiappan *et al.* (2002) made based on isotopic studies during 1994–1995. For the wells W1–W5, Nachiappan *et al.* (2002) estimated higher proportion of bank filtrate (80%) during monsoon and a lower proportion (20%) during non-monsoon. Although this difference in conclusions could be reflecting actual changes in the local hydrology in the lake bank aquifers over the years, a few important differences also exist between present data and analysis and that of Nachiappan *et al.* (2002). The first and foremost difference is that both the lake and the groundwater were isotopically lighter in the present study than what was observed during 1994–1995, either because of change in rainfall pattern in the region or because of a change in the origin of groundwater coming to the lake catchment region. Secondly, Nachiappan *et al.* (2002) sampled at multiple locations in the lake at different depths and took the average of the isotope values. Investigations at Lake Tegel in Berlin (Fritz *et al.*, 2002) show that the majority of the infiltration at lake banks is likely to be from the top epilimnion zone of the lake. Therefore, water near the lake surface close to the infiltration wells is more likely to be representative of infiltrating water rather than average values of samples across the lake. We tested water samples from various points across the lake and observed differences in  $\delta^{18}\text{O}$  value of up to 0.4‰ between various points. Therefore, our analysis based on the lake surface water close to the wells would lead to different results than the average derived from sampling various points in the lake as adopted by Nachiappan *et al.* (2002). Thirdly, groundwater samples in the present study were collected from sources close to the LBF wells, whereas previous groundwater data was collected from the springs in the whole region, many of which dried up in recent years.

In terms of organic content, the lake has become one of the cleaner lakes in the world. The average DOC of the lake – 3.1 mg/L (Table 3.5) was much lower than typical DOC concentrations in most lakes in the world. Median DOC of ~7,541 lakes in the world is 5.7 mg/L (Sobek *et al.*, 2007). The SUVA values observed in this present study were also lower than the values observed for lake water and bank filtrate in Lake Tegel (Grünheid *et al.*, 2005), and were also lower than the values observed in deep groundwaters (Inamdar *et al.*, 2012) suggesting the dominance of low molecular weight aliphatic compounds in Nainital waters.

## 3.7 CONCLUSIONS

Recent isotope studies showed that during the present study period, the LBF wells at Naini lake bank abstracted different proportions of bank filtrate and these proportions were not necessarily determined by the distance from the lake. Wells W2 and W4 abstracted ~80% bank filtrate almost throughout the year. Wells W1, W3, and W7, although located at similar distances (12–15 m) as well W2 (14.9 m), abstracted >50% bank filtrate during non-monsoon season but mostly groundwater during monsoon seasons. Wells W5, W6, W8, and W9, located >40 m from the lake, abstracted >75% groundwater almost throughout the year. One possible reason for such unusual hydrology is the presence of the Naini fault and other sub-faults very close to the well field. Groundwater seepage from these faults can affect the flow pattern of bank filtrate in the lake bank aquifer. In addition, steep slopes on the north, west, and south sides of the well field also complicate the flow patterns.

This study showed that the water quality of Lake Naini considerably improved with lower coliforms, turbidity, and organics and higher DO as a result of various cleaning efforts including hypolimnetic aeration. The water quality of the wells continues to be good, but a few occasional contaminations are observed for brief periods.

The waters in the region had calcium, magnesium, hydrogen carbonate and sulphate as the predominant ions with a calcium:magnesium ratio of ~0.75 in all the waters. The data suggests the predominant mineral responsible for this mineralization of water to be magnesium and carbonate based.

The bank filtrate had much better water quality than the groundwater in terms of inorganic ion concentrations throughout the year. The wells W2 and W4 should be pumped more to obtain a better quality bank filtrate. Abstraction from other wells can be regulated with seasonal changes to obtain the maximum amount of bank filtrate. Net abstraction of bank filtrate, however, should not increase by more than two times, beyond which water level of the lake and groundwater may go down making the system unsustainable.

Overall the lake bank filtration system in Nainital is highly effective in providing drinking quality water, provided contamination through groundwater can be kept in check.

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## 3.8 REFERENCES

- AHEC (2002). Detailed project report on conservation and management plan for Nainital Lake. AHEC/2002, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Uttaranchal (now Uttarakhand), India.
- APHA, AWWA and WPCF (1995, 1998, 2005). Standard methods for the examination of water and wastewater, 19th, 20th and 21st edn., American Public Health Association, Washington DC, United States.
- Ashraf Z. (1978). A geological report on the drilling explorations carried out for the study of Nainital hill slope stability. Nainital district, U.P. Report of Geological Survey of India, Northern Region, Lucknow, India.
- Bureau of Indian Standards (BIS) 10500 (2012). Drinking Water – Specification. Indian Standard, 2nd Revision. Bureau of Indian Standards, New Delhi, India.
- Census of India (2011). Office of the Registrar General and Census Commissioner, India. <http://www.censusindia.gov.in> (accessed 28 August 2014).
- Chakrapani G. J. (2002). Water and sediment geochemistry of major Kumaun Himalayan lakes, India. *Environmental Geology*, **43**(1–2), 99–107.
- Chauhan A., Fortenberry G. Z., Lewis D. E. and Williams H. N. (2009). Increased diversity of predacious *Bdellovibrio*-Like Organisms (BLO) as a function of eutrophication in Kumaon lakes of India. *Current Microbiology*, **59**(1), 1–8.
- Das B. K., Singh M. and Borkar M. D. (1994). Sediment accumulation rate in lakes of Kumaun Himalaya, India using  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$ . *Environmental Geology*, **23**(2), 114–118.
- Das B. K., Singh M. and Van Grieken R. (1995). The elemental chemistry of sediments in the Nainital lake, Kumaun Himalaya, India. *Science of the Total Environment*, **168**(1), 85–90.
- Dash R. R., Mehrotra I., Kumar P. and Grischek T. (2008). Lake bank filtration at Nainital, India: Water quality investigations. *Hydrogeology Journal*, **16**(6), 1089–1099.
- Dua V. K., Kumari R., Johri R. K., Ojha V. P., Shukla R. P. and Shukla V. P. (1998). Organochlorine insecticide residues in water from five lakes of Nainital (U.P.), India. *Bulletin of Environmental Contamination and Toxicology*, **60**(2), 209–215.
- Fritz B., Sievers J., Eichhorn S. and Pekdeger A. (2002). Geochemical and hydraulic investigations of river sediments in a bank filtration system. In: Management of aquifer recharge for sustainability, P. Dillon (ed.), Swets and Zeitlinger, Lisse, The Netherlands, pp. 95–100.
- GoogleMaps (2013). <http://maps.google.com/> (accessed 1 October 2014).
- Grünheid S., Amy G. and Jekel M. (2005). Removal of bulk dissolved organic carbon (DOC) and trace organic compounds by bank filtration and artificial recharge. *Water Research*, **39**(14), 3219–3228.
- Gupta P. K. and Pant M. C. (1983). Microbenthos of lake Naini Tal (U.P., India) with particular reference to pollution. *Water, Air & Soil Pollution*, **19**(4), 397–405.
- Gupta R., Bhagat P., Joshi M., Inaotombi S. and Gupta P. K. (2010). Heavy metal pollution status of Lake Nainital, Uttarakhand. *Indian Journal of Scientific Research*, **1**(1), 15–19.
- Gupta R. and Gupta P. K. (2012). The impact of artificial circulation on phytoplankton community on a fresh water eutrophic lake. *Journal of Ecophysiology and Occupational Health*, **12**(3–4), 1–20.
- Hoffmann A. and Gunkel G. (2011). Bank filtration in the sandy littoral zone of Lake Tegel (Berlin): Structure and dynamics of the biological active filter zone and clogging processes. *Limnologia*, **41**(1), 10–19.
- Inamdar S., Finger N., Singh S., Mitchell M., Levia D., Bais H., Scott D. and McHale P. (2012). Dissolved organic matter (DOM) concentration and quality in a forested mid-Atlantic watershed, USA. *Biogeochemistry*, **108**(1–3), 55–76.
- IMD (2013). Mean rainfall data of Nainital District. HYDROMET Division, Indian Metrological Department, New Delhi. <http://www.imd.gov.in/section/hydro/distrainfall/webbrain/uttarakhand/nainital.txt> (accessed 20 August 2014).
- Juhász-Holterman M. H. A., Peters J. H. and Geets J. J. G. M. (1998). Artificial recharge of a lake excavated for gravel extraction. In: Artificial recharge of groundwater, J. H. Peters *et al.* (eds), Balkema, Rotterdam, pp. 237–242.
- Kumar A. (2008). Hypolimnetic withdrawal for lake conservation. In: Proceedings of Taal2007: The 12th World Lake Conference, M. Sengupta and R. Dalwani (eds), Ministry of Environment and Forests, New Delhi, India, pp. 812–818.
- Kumar B., Nachiappan R. P., Rai S. P., Sarvanakumar U. and Navada S. V. (1999). Improved prediction of life expectancy for a Himalayan lake: Nainital, U.P., India. *Mountain Research and Development*, **19**(2), 113–121.
- Kivimäki A. L., Lahti K., Hatva T., Tuominen S. M. and Miettinen I. T. (1998). Removal of organic matter during bank filtration. In: Artificial recharge of groundwater, J. H. Peters *et al.* (eds), Balkema, Rotterdam, The Netherlands, pp. 107–112.

- Massmann G., Sültenfuss J., Dünnebier U., Knappe A., Taute T. and Pekdeger A. (2008). Investigation of groundwater residence times during bank filtration in Berlin: A multi-tracer approach. *Hydrological Processes*, **22**(6), 788–801.
- Miettinen I. T., Martikainen P. J. and Vartiainen T. (1994). Humus transformation at the bank filtration water plant. *Water Science and Technology*, **30**(10), 179–187.
- Nachiappan R. P. and Kumar B. (1999). Study of the interconnection between a lake and surrounding springs using environmental tracers. Proceedings IUGG 99 Symposium HS4, Birmingham, IAHS (258), pp. 215–219.
- Nachiappan R. P., Kumar B. and Manickavasagam R. (2002). Estimation of sub-surface components in the water balance of Lake Nainital (Kumaun Himalaya, India) using environmental isotopes. *Hydrological Sciences Journal*, **47**, 41–54.
- Pant M. C., Gupta P. K., Pande J., Sharma P. C. and Sharma A. P. (1981). Aspects of water pollution in Lake Nainital, U.P., India. *Environmental Conservation*, **8**(2), 113–117.
- Purohit R. and Singh S. P. (1981). Seasonal variation in physico-chemical limnology of shallow zones in Nainital Lake, Western Himalaya (India). *Proc. Indian Natn. Sci. Acad.*, **B47**(2), 194–203.
- Purohit R., Singh S. P. and Upreti N. (1986). Effect of non-removal of the macrophytic biomass on the characteristics of water and plant community in Lake Naini Tal, U.P., India. *Internationale Revue Der Gesamten Hydrobiologie*, **71** (2), 245–257.
- Purushothaman P., Mishra S., Das A. and Chakrapani G. J. (2012). Sediment and hydro biogeochemistry of Lake Nainital, Kumaun Himalaya, India. *Environmental Earth Sciences*, **65**(3), 775–788.
- Rawat J. S. (1987). Morphology and morphometry of the Naini Lake, Kumaun, Lesser Himalaya. *Journal of the Geological Society of India*, **30**(6), 493–498.
- Sandeep C. (2011). Lake bank filtration induced transport of microorganisms. M. Tech. Dissertation, Department of Civil Engineering, Indian Institute of Technology Roorkee, Uttarakhand, India.
- Sharma A. P., Jaiswal S., Negi V. and Pant M. C. (1982). Phytoplankton community analysis in lakes of Kumaun Himalaya. *Archiv für Hydrobiologie*, **93**, 173–193.
- Sharma V. K. (2001). Geological investigations at the proposed water treatment plant (WTP) site at Children Park (Flats), Nainital Township, Kumaun Himalaya. Report of Geological Survey of India, Northern Region, Lucknow, India.
- Shukla U. and Gupta P. K. (2001). Assemblage of ciliated protozoan community in a polluted and non-polluted environment in a tropical lake of central Himalaya: Lake Naini Tal India. *Journal of Plankton Research*, **23**(6), 571–584.
- Sobek S., Tranvik L. J., Prairie Y. T., Kortelainen P. and Cole J. J. (2007). Patterns and distribution of dissolved organic carbon: An analysis of 7500 widely distributed lakes. *Limnology and Oceanography*, **52**(3), 1208–1219.
- Valdiya K. S. (1980). Geology of Kumaun Lesser Himalaya. Gyānodaya Prakāshan, Nainital, India.
- Valdiya K. S. (1988). Geology and Natural Environment of Nainital Hills, Kumaun Himalaya. Gyānodaya Prakāshan, Nainital, India.
- Weishaar J. L., Aiken G. R., Bergamaschi B. A., Fram M. S., Fujii R. and Mopper K. (2003). Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. *Environmental Science and Technology*, **37**(20), 4702–4708.
- Williams D. (2007). Lake aeration system of Nainital, India. [http://www.paradisew.com/cases/lake\\_nainital\\_in.php](http://www.paradisew.com/cases/lake_nainital_in.php) (accessed 24 August, 2014).